

All Hadronic Searches with CMS

Kenichi Hatakeyama

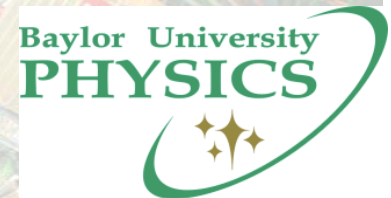
Baylor University

For the CMS Collaboration

Workshop on SUSY with 5 / fb at the LHC

Brookhaven National Laboratory

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CMS All Hadronic Analyses

CMS has four complementary analyses searching for Supersymmetry in all-hadronic signatures:

- ❑ Search with Jets + MHT (SUS-12-011)
- ❑ Search with M_{T2} (SUS-12-002)
- ❑ Search with Razor variables (SUS-12-005)
- ❑ Searches with α_T (SUS-11-003)

Looking at different kinematic features of signal events.

All these searches are performed in a generic-way, thus sensitive to any new physics with multijets + MET

- ❑ All the public results can be found on:
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>

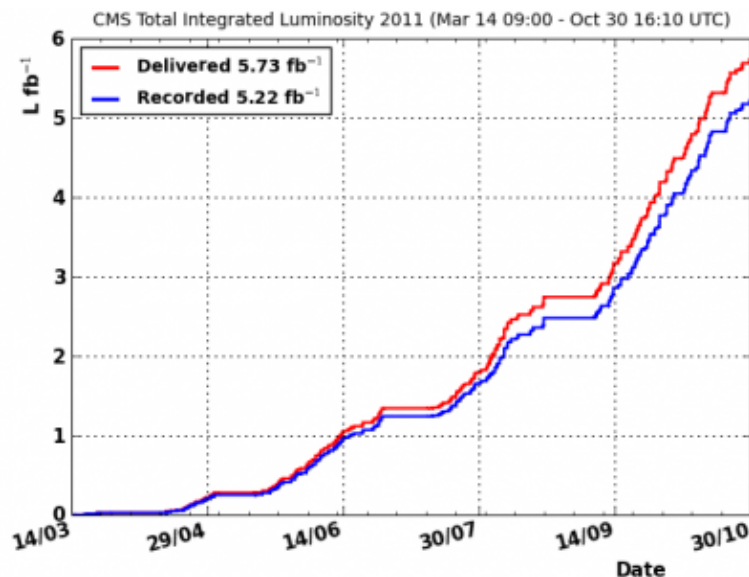
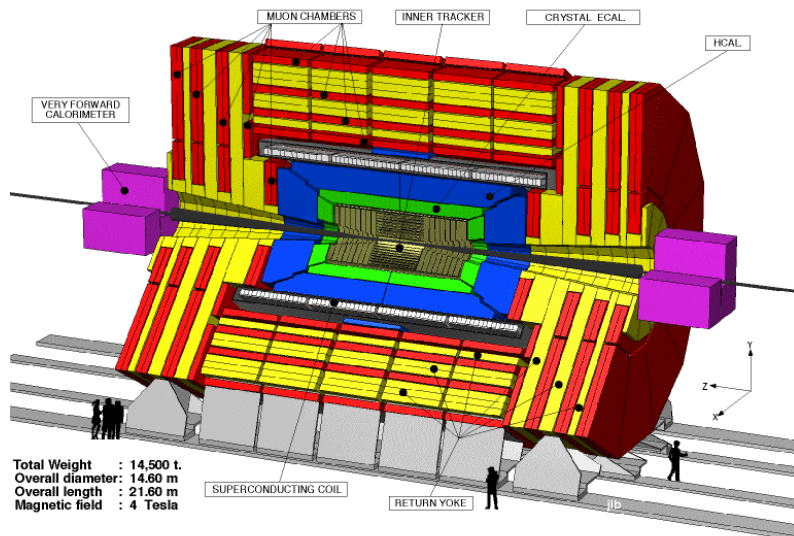


CMS Performance



The top-left image is an aerial photograph of a rural landscape with a circular white highlight. The bottom-left image is a smaller version of the same aerial photograph. The bottom-right image is a 3D rendering of the CMS detector's interior, showing a complex arrangement of colorful components (red, yellow, green, blue) and a central yellow structure.

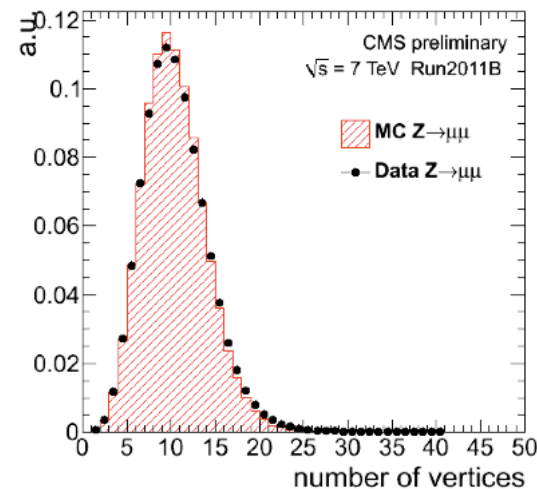
CMS in 2011



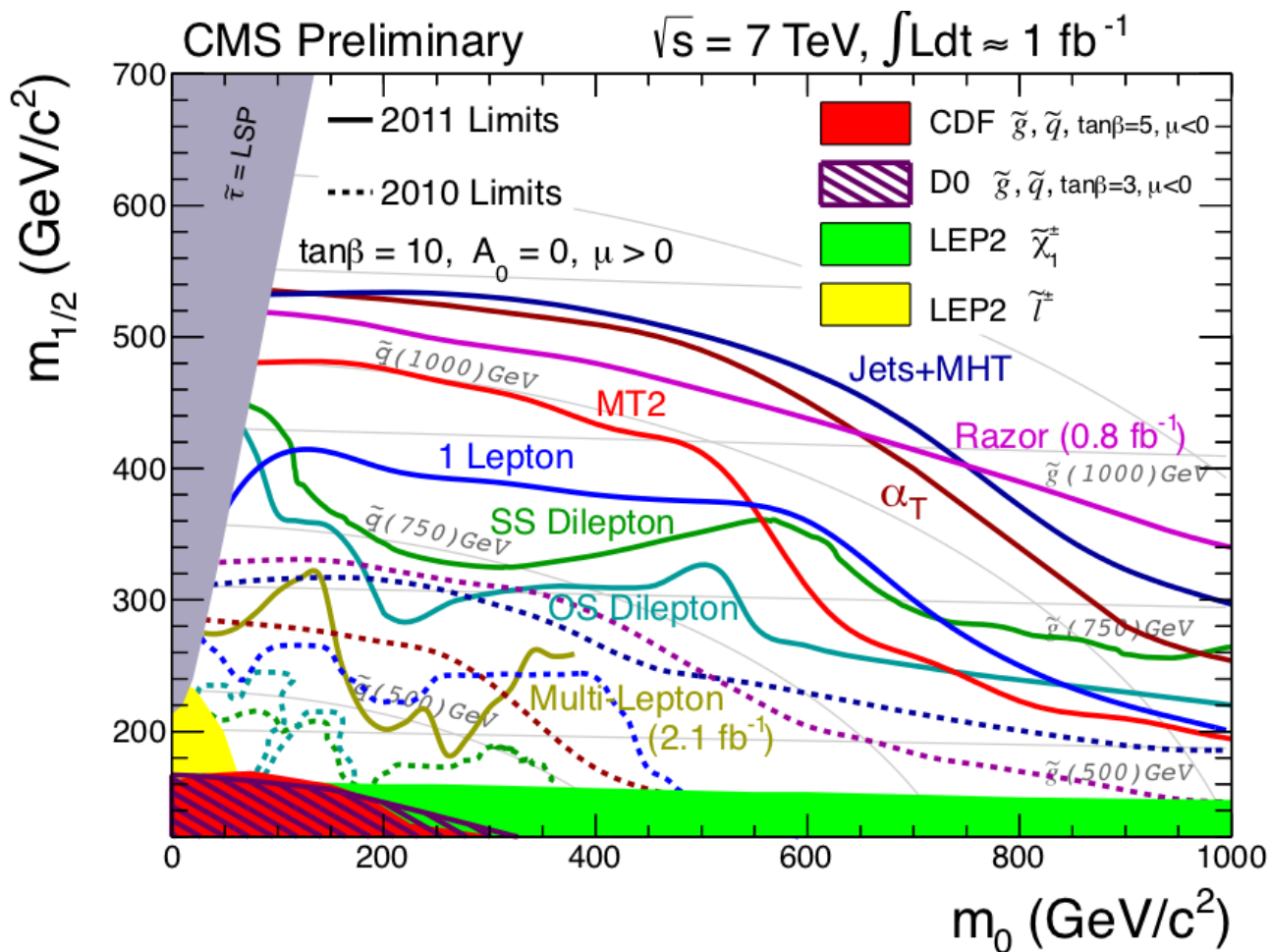
- More than 5 fb^{-1} collected @ 7 TeV
- Peak lumi $3.5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- Data taking efficiency: 90%
- Mean pileup: ~ 10

And, in 2012 we already have $\sim 1 \text{ fb}^{-1}$ of 8 TeV data with peak lumi $3.5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$.

Keep us happily busy!



Where We Were Last Fall!



How much more did we learn since then?



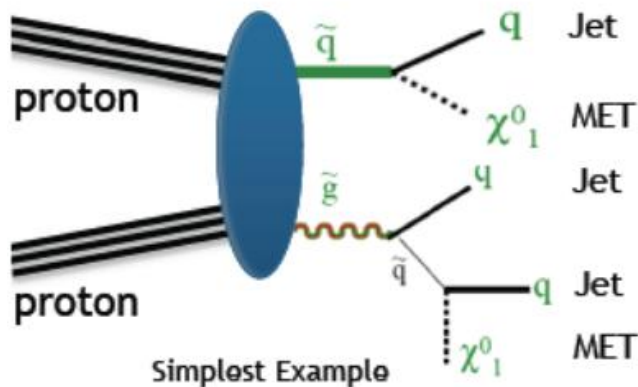
Searches with Jets + MHT



The slide features a title 'Searches with Jets + MHT' in bold black font. The background is a collage of three images: an aerial photograph of a rural landscape with a white circle highlighting a search area, a horizontal green bar, and a 3D rendering of the ATLAS detector's interior showing its complex structure and central tunnel.

Jets + MHT: Introduction

- A generic search for large missing transverse momentum in events containing multijets is “motivated” by R-parity conserving SUSY
 - strong production of $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$ pairs



$$H_T = \sum_i^{jets} |\vec{p}_{T,i}|$$

Characterize visible energy of the event

$$\cancel{H}_T = \left| -\sum_i^{jets} \vec{p}_{T,i} \right|$$

Characterize energy carried by undetected particle

SM Backgrounds

- Z(vv)+jets
- W/tt+jets with W(e/μ/τ ν)
- QCD multijet

- The key is that we understand SM backgrounds including the MH_T arising from detector effects and reconstruction failure

Analysis Strategy

□ Sample selection

- At least 3 jets with $p_T > 50$ GeV & $|\eta| < 2.5$
- Veto events with isolated e & μ : reduce W/top background
 - $p_T > 10$ GeV, $|\eta| < 2.5$, isolation < 0.2
- $\Delta\Phi(MH_T, \text{Jets}_{123}) > (0.5, 0.5, 0.3)$: reduce QCD background
- H_T - scalar sum of all jets with $p_T > 50$ & $|\eta| < 2.5$
- MH_T - magnitude of vector sum of all jets with $p_T > 30$ GeV & $|\eta| < 5$

□ Analysis strategy

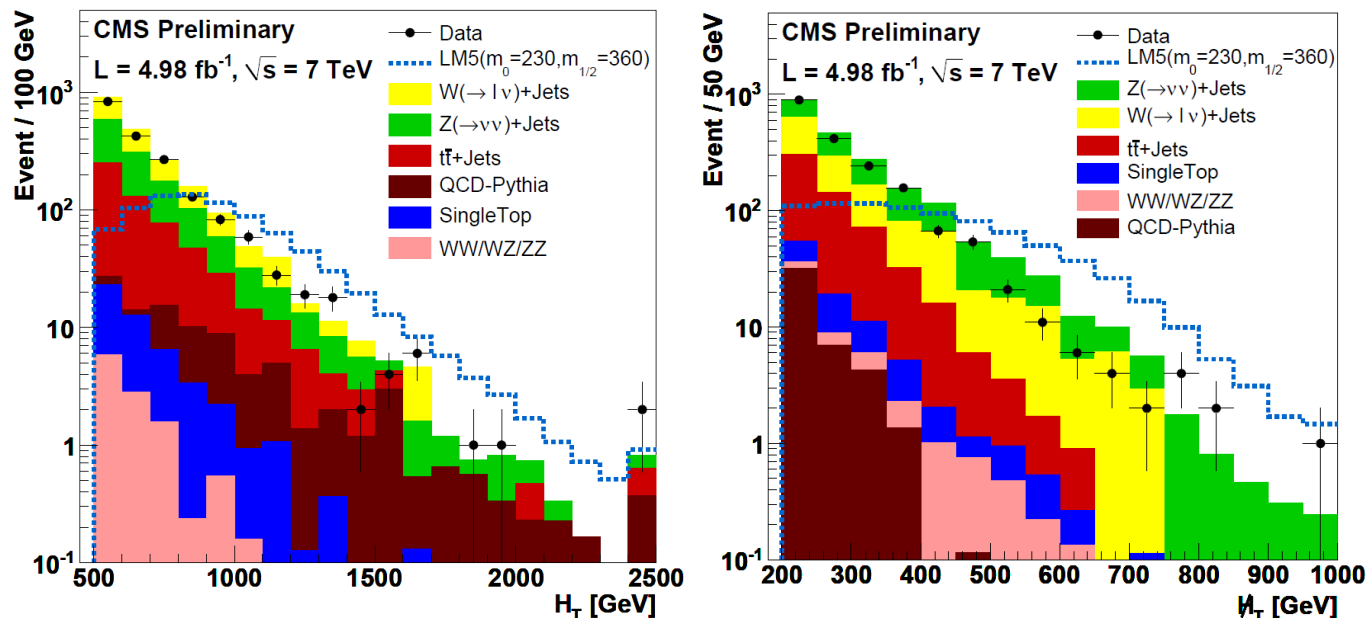
- An inclusive analysis based on H_T and MH_T

□ Search regions in H_T & MH_T

- Baseline
($H_T > 500$ & $MH_T > 200$ GeV)
- 14 exclusive bins in H_T & MH_T

MHT→ HT ↓	200-350	350-500	500-600	>600
500-800	bin 1	bin 2	bin 3	bin 4
800-1000	bin 5	bin 6	bin 7	bin 8
1000-1200	bin 9	bin 10	bin 11	
1200-1400	bin 12	bin 13		
>1400	bin 14			

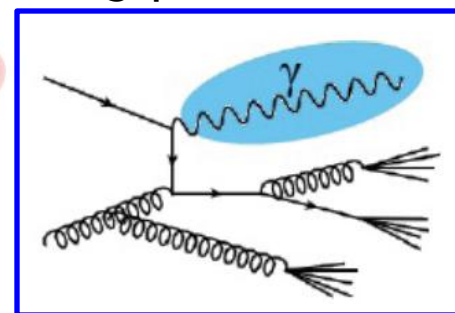
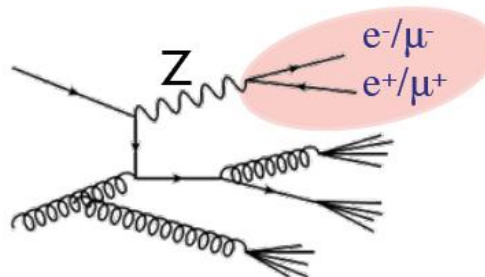
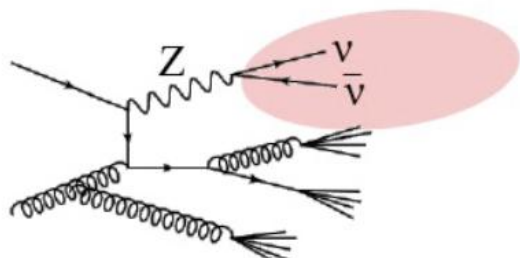
Data and MC Comparisons



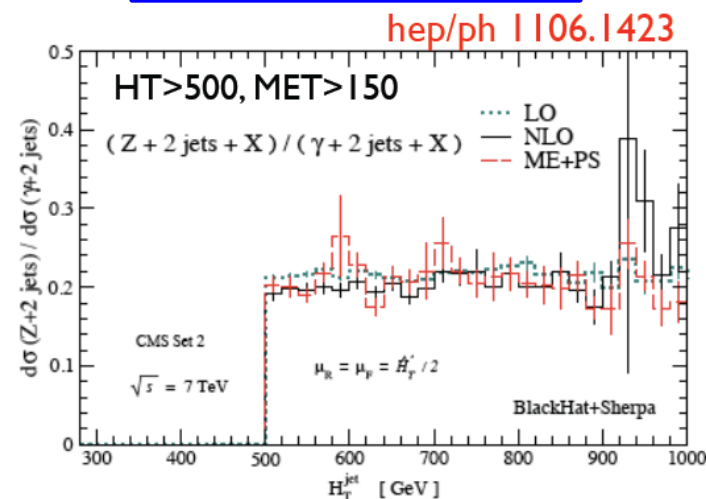
- The H_T & M_{H_T} distributions are well described by CMS simulation
- Evaluating systematics for both the generator-level information and detector simulation accurately for not trivial.
- We estimate the backgrounds from collision data.

Z(vv)+Jets from γ +Jets

- A straightforward method is to use Z (ll) +Jets events
 - suffers from lack of statistics in tighter search regions and is used only to cross-check the background prediction using γ + Jets



- At high p_T , the Z+jets/ γ +jets ratio depends mainly on the EWK characteristics of the event
- Hadronic part of the event is independent of whether the boson is Z or γ
- Theoretical uncertainty (from BlackHat) :
 - EWK corr. at higher orders
 - large QCD logarithm terms



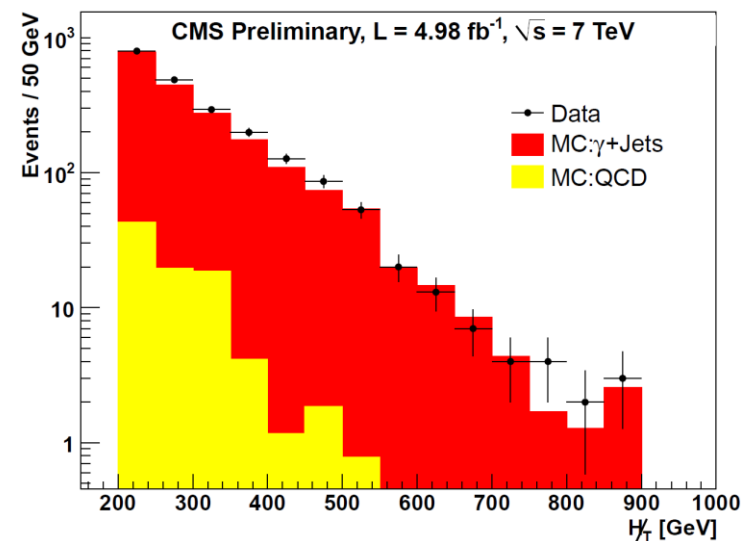
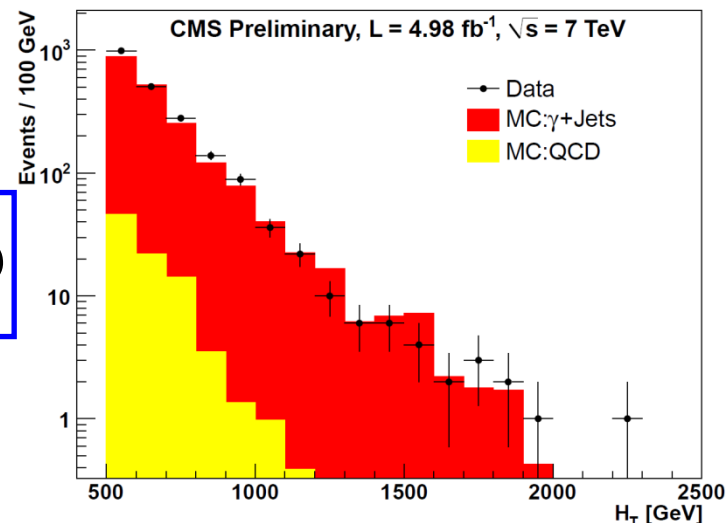
Sizable theory uncertainty: 21-42%. The reduction is critical for future searches.

Z($\nu\nu$)+Jets from γ +Jets

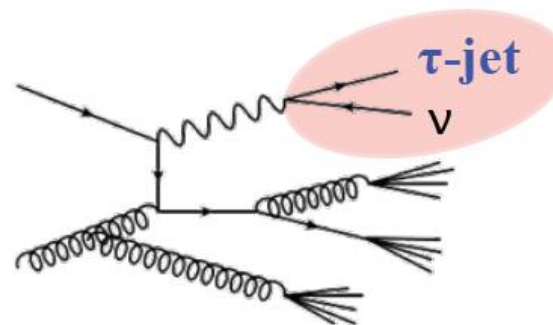
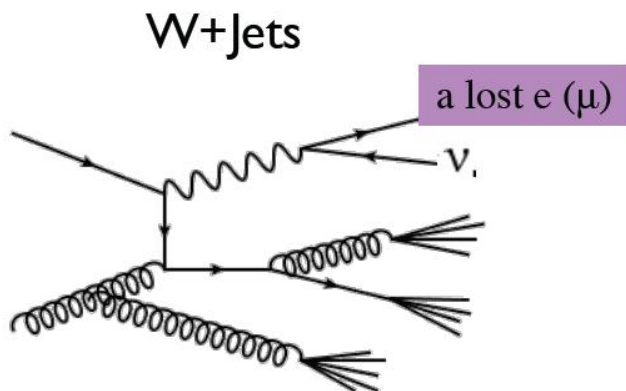
- Start with a γ +jets control sample : $p_T(\gamma) > 100$ GeV.

$$N^{Z(\nu\nu)+jets}(\text{data}) = \frac{Z + jets}{\gamma + jets} \cdot \text{Purity} \cdot N^{\gamma+jets}(\text{data})$$

- Subtract contributions from secondary photons : purity=98-99% as measured from data using isolation
- Correct for photon reco & isolation efficiencies measured from data using tag-and-probe method on Z(ee)+jets
- Scale with Z($\nu\nu$)+jets/ γ +jets production ratio
- Predictions of Z($\nu\nu$)+jets using $\mu+\mu$ -+jets are compatible with those from γ +jets within uncertainties



W/Top(e/ μ / τ + ν)+Jets



Lost lepton background:

- Leptons failing the lepton veto criteria contribute to BG:
 - the lepton is not reconstructed, not isolated, out of acceptance

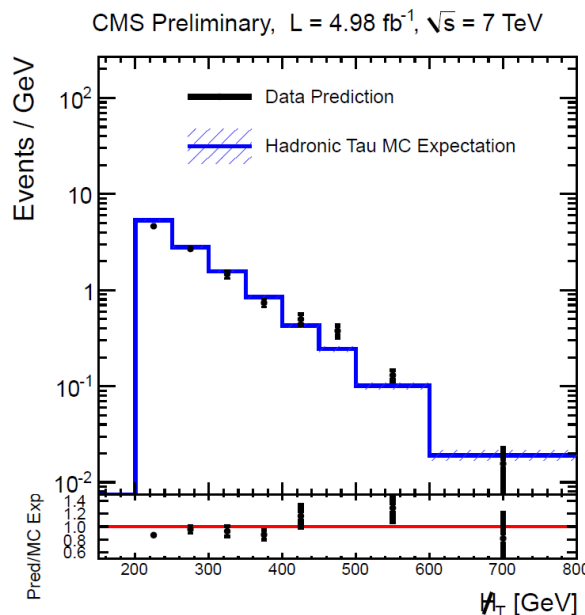
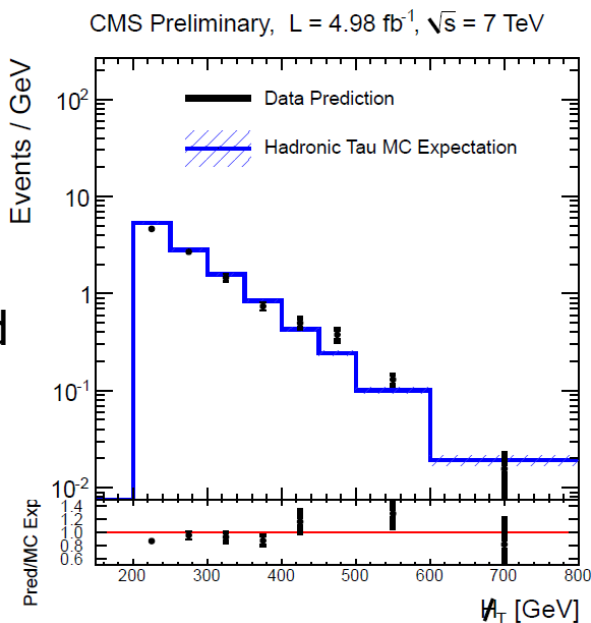
Hadronic tau background:

- Tau decaying hadronically contribute to BG with one tau-jet:
 - the lepton is not reconstructed, not isolated out of acceptance

Top / W + hadronic tau + ν + Jets

- Start with a μ +jets sample
- Replace the μ by τ response template derived from MC
- Recalculate H_T and MH_T including this expected energy from τ
- Correct for muon acceptance, trigger, reco, & iso efficiency $BR(W \rightarrow \tau \rightarrow \text{hadrons})/BR(W \rightarrow \mu)$

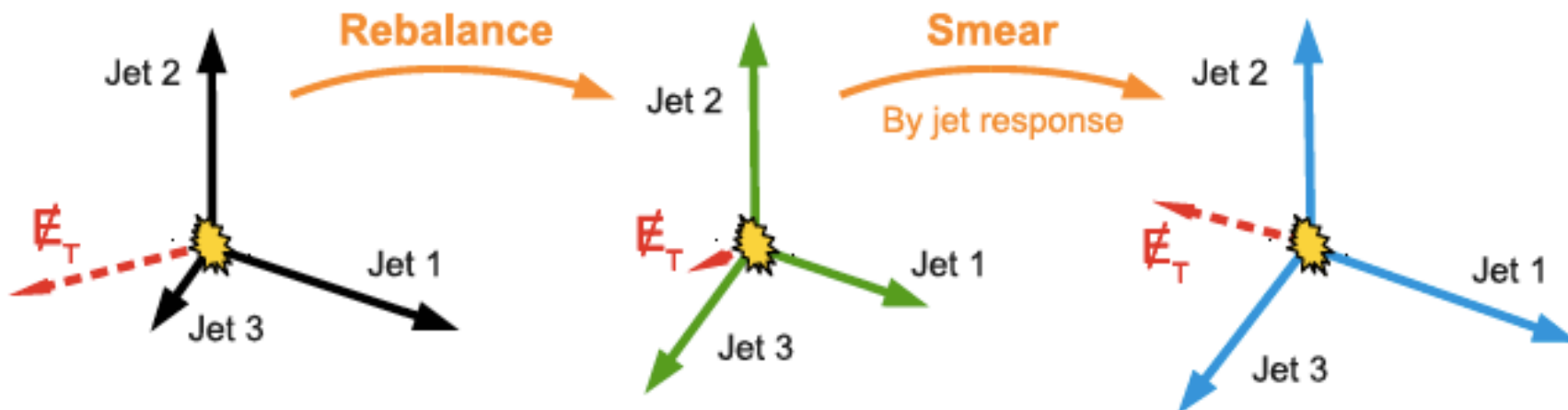
Method tested
with MC



Data-driven
estimate
consistent
with MC
expectation

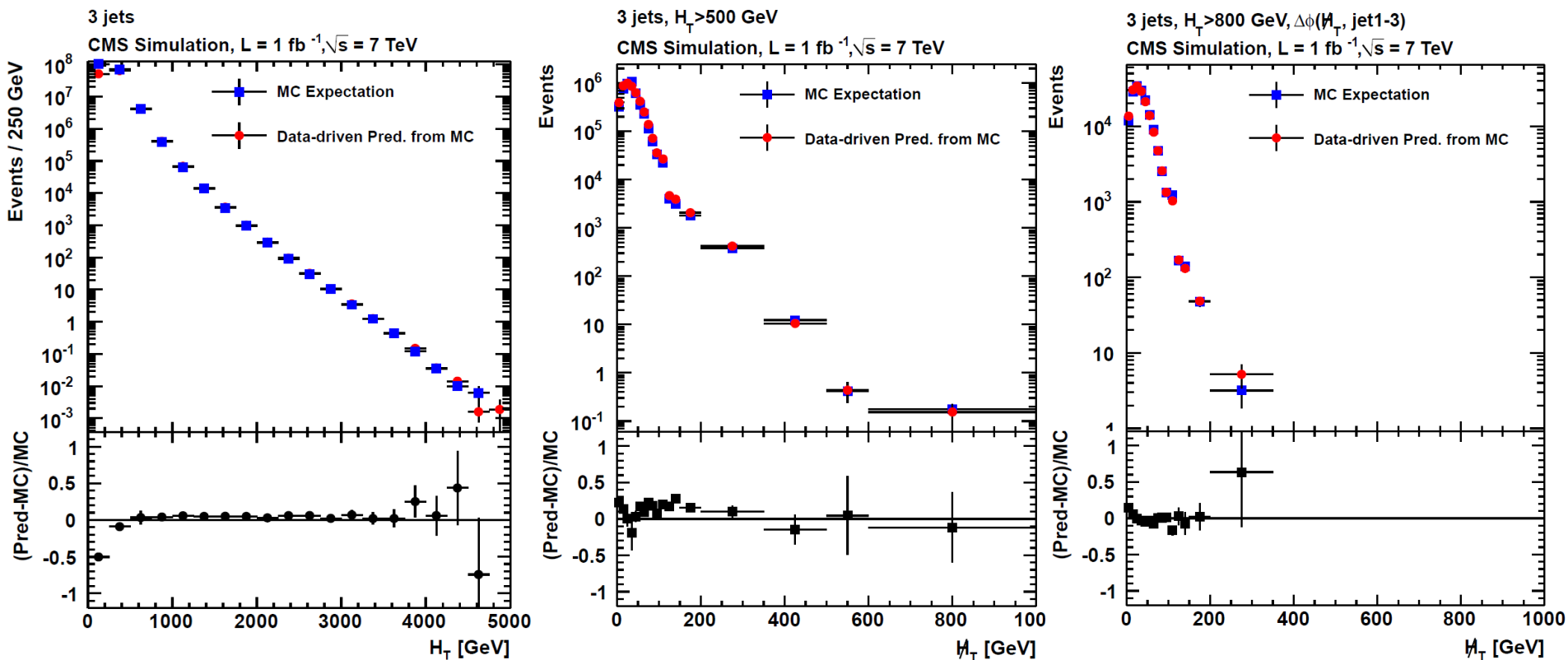
QCD : ReBalance + Smear

- QCD multijet events are balanced at the parton level
- An imbalance is introduced by the mis-measurement of jets due to detector response fluctuations or heavy-flavor jets



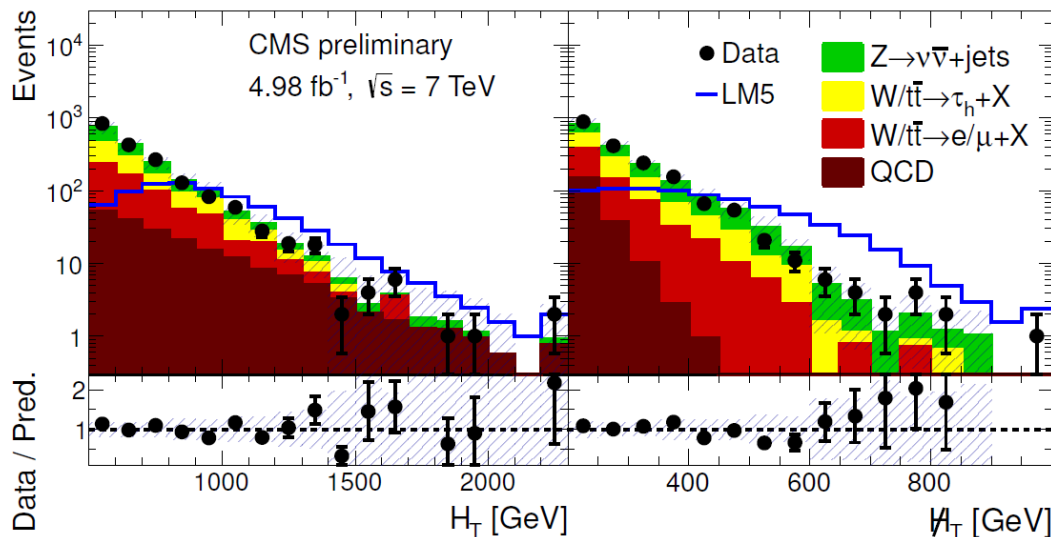
- Rebalance : Particle level jet p_T is restored from detector level inclusive multijet data using a kinematic fit subject to constraint $M_{H_T}=0$ (using jet resolution functions derived from MC but corrected to match data)
- Smear : “Rebalanced” events are smeared using the measured jet resolution functions including the tails

QCD : ReBalance + Smear

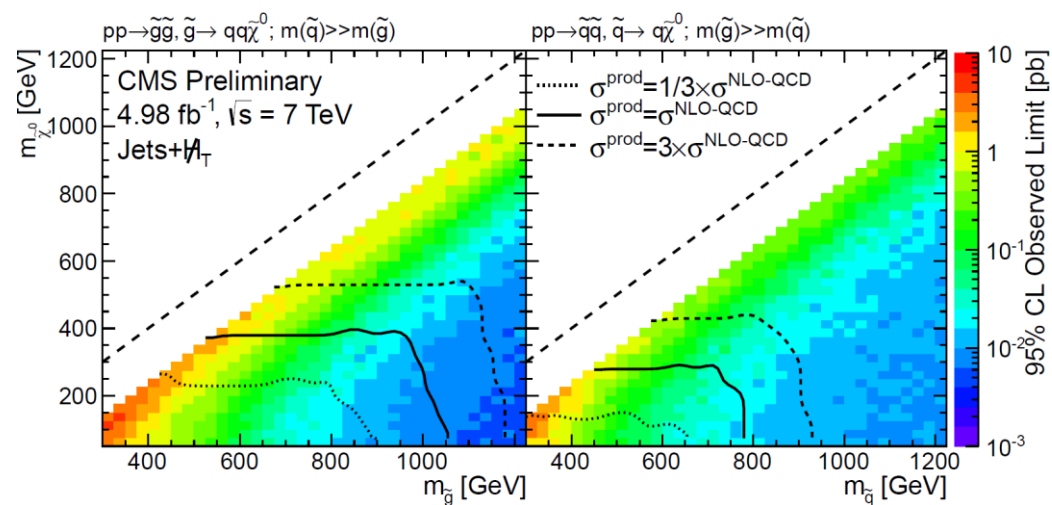
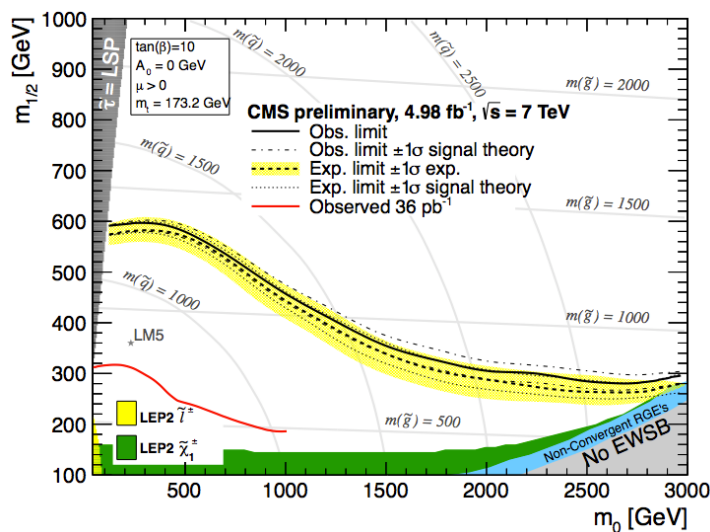
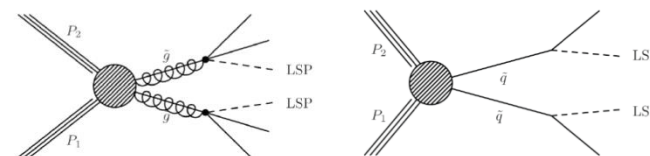


- Method validated using the MC Simulation
- Total systematic uncertainty 60-70%
 - Closure test, jet resolution measurements, pileup effects, heavy-flavor modeling

Results & Interpretations



Observations
consistent with
SM expectations





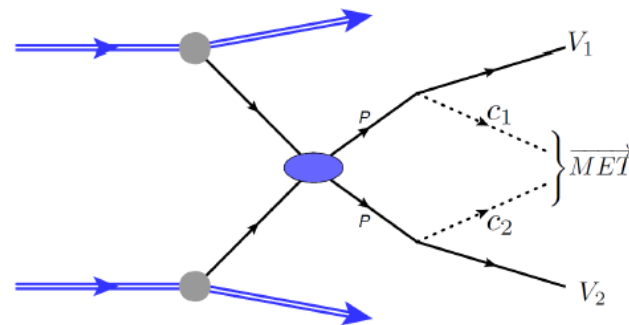
Searches with MT2



Searches with M_{T2}

- The M_{T2} is a generalization of the transverse mass for decay chains with two unobserved particles. typical in R-parity conserving SUSY

$$M_{T2} = \min_{p_T^{c1} + p_T^{c2} = \cancel{p}_T} \left[\max \left(m_T^{(1)}, m_T^{(2)} \right) \right]$$



- For the simplified case of no ISR and zero masses:

$$(M_{T2})^2 \simeq 2p_T^{vis(1)} p_T^{vis(2)} (1 + \cos \phi_{12})$$

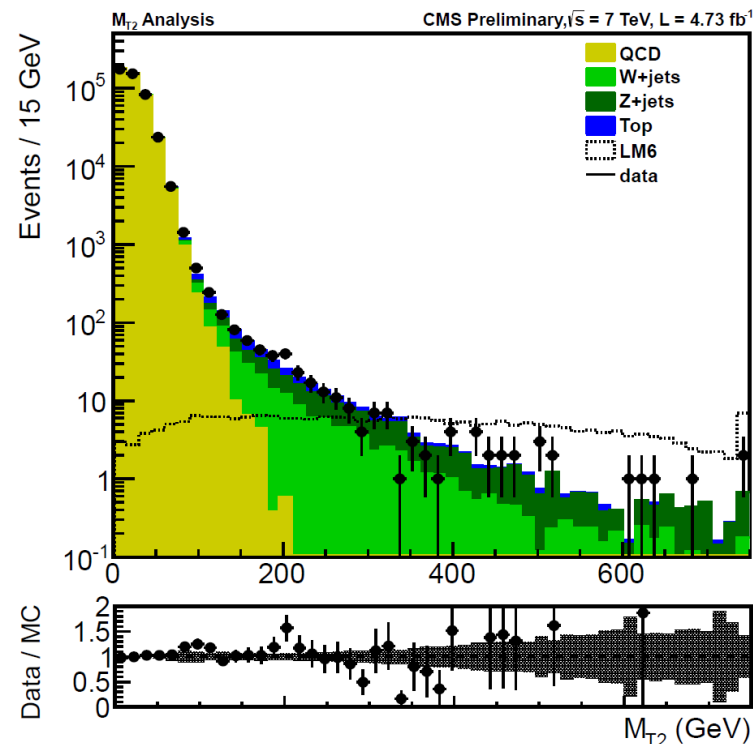
- Multijet events divided into 2 massless pseudo-jets using a hemisphere algorithm
- $M_{T2} \sim MET$ for symmetric SUSY-like topologies
- M_{T2} is a QCD killer
 - $MT2 \approx 0$ for back-to-back events with no genuine MET
 - $MT2 < MET$ still highly suppressed for nearly back-to-back QCD mismeasurements
- M_{T2} provides very good discriminating power between SM and SUSY-like events, and in this analysis is used as a discovery variable

Analysis Strategy

- ❑ Multi-bin analysis based on H_T & M_{T2}
- ❑ Background estimated in each bin using data-driven methods
- ❑ There are two analyses targeting complementary SUSY topologies
 - **MT2 analysis** and **MT2b analysis**:
See Keith's talk for MT2b

MT2 analysis

- ❑ At least 3 jets
- ❑ 2 H_T bins [750-950-:GeV], 5 M_{T2} bins [150-200-275-375-500-:GeV]
- ❑ W+jets and $Z \rightarrow \nu\nu$ main backgrounds (and QCD)
- ❑ Optimized for signals with large MET (low m_0) [MT2b for high m_0]



- ❑ **Background estimation:**
 $Z \rightarrow \nu\nu$: from $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$
 W+jets: similar to prev. search
 QCD: Factorization method

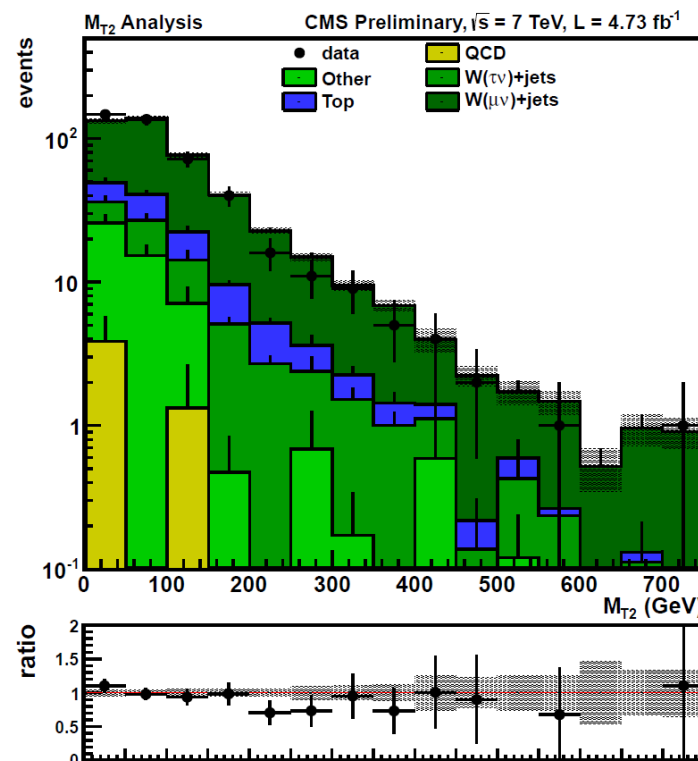
$Z \rightarrow \nu\nu$ from $W \rightarrow l\nu$

- Predict $Z(\nu\nu)+\text{jets}$ from photon+jets and $W(l\nu)+\text{jets}$ events

$Z(\nu\nu)+\text{jets}$ from $W(l\nu)+\text{jets}$

- $W(\rightarrow l\nu)+\text{jets}$ enriched sample obtained by using all selection cuts and:
 - One μ with $p_T > 10$ GeV
 - B-tag veto to suppress $t\bar{t}$ bar
 - $m_T(W) < 100$ GeV to reduce signal contamination
- $Z(\rightarrow \nu\nu)+\text{jets}$ estimated as

$$N_{Z(\rightarrow \nu\nu)} = N_{W(\rightarrow l\nu)} \frac{1}{(\epsilon_{\text{acc}} \epsilon_{\text{reco/iso}})} R_{\text{MC}}$$
 - Muon acceptance from MC
 - Muon reco/iso efficiencies obtained from Tag&Probe in data
 - R_{MC} corrects for: kinematic differences, cross-sections, M_T & b-tag veto efficiencies
 - Backgrounds subtraction by MC, except $t\bar{t}$ bar, which is estimated using $t\bar{t}$ bar enriched data by requesting 1 b-tag



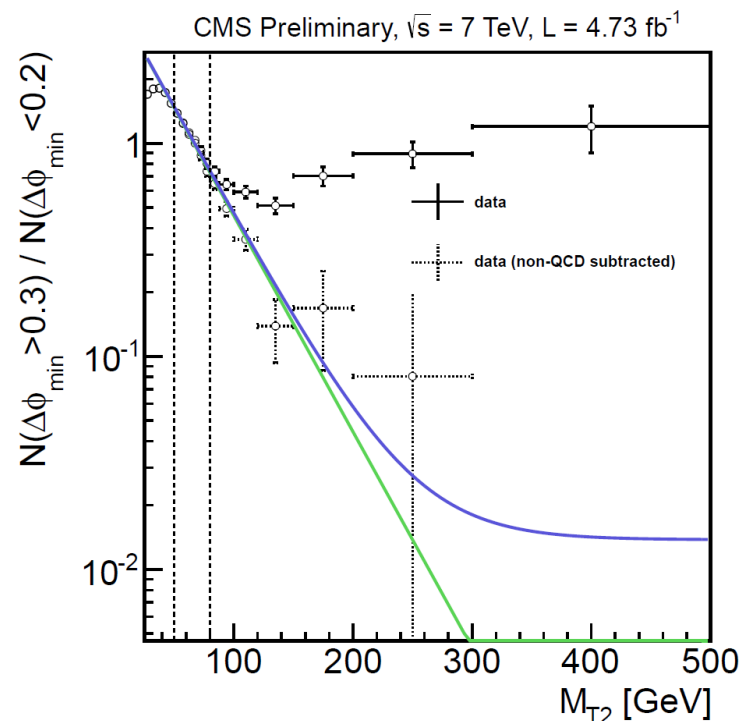
Consistent with the estimation from photon+jets
Weighted average to give the final $Z \rightarrow \nu\nu$ estimation

QCD factorization method:

- Predict signal region (high M_{T2} , $\phi_{\min} > 0.3$) from QCD-rich region (high M_{T2} , $\phi_{\min} < 0.2$)
- Exponential functional form motivated from simulation

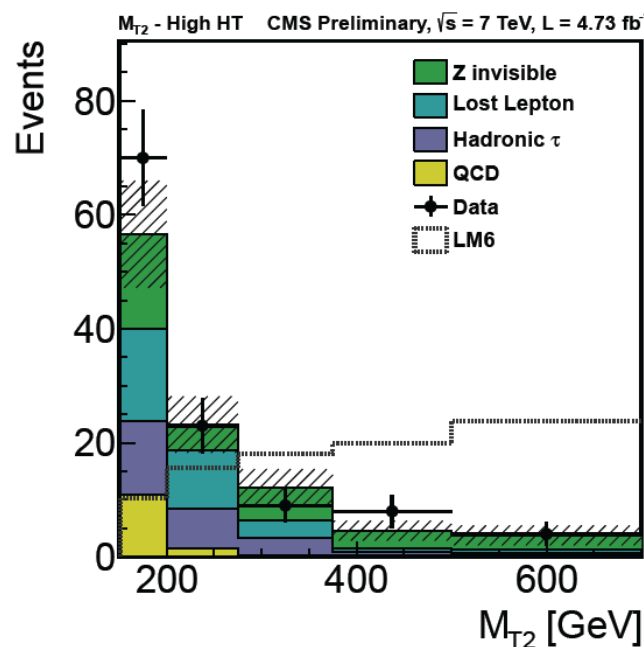
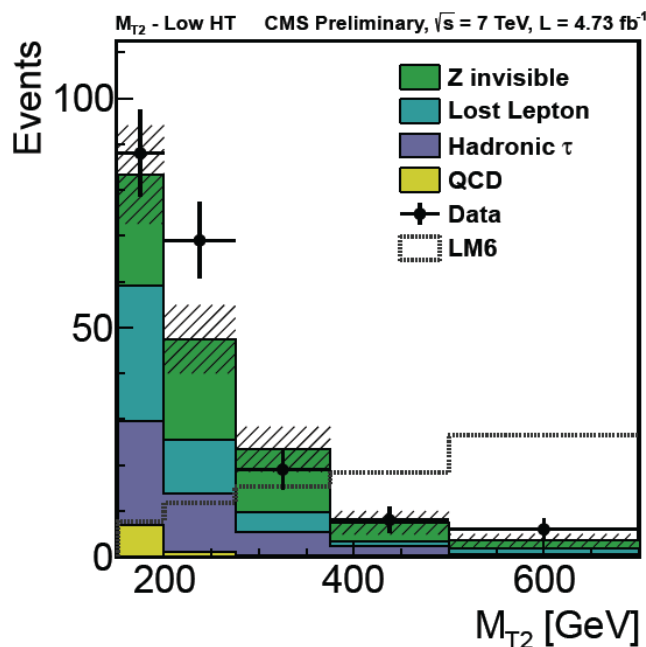
$$r(M_{T2}) = \frac{N(\Delta\phi_{\min} > 0.3)}{N(\Delta\phi_{\min} < 0.2)} = e^{a-b \cdot M_{T2}} + c$$

- Fit region $50 < M_{T2} < 80$ GeV to have minimal contamination from non-QCD data
- EWK background is subtracted from data, and a fit is performed to extract a and b
- Constant term c taken conservatively as the value of the fitted exponential at $M_{T2} = 250$ GeV





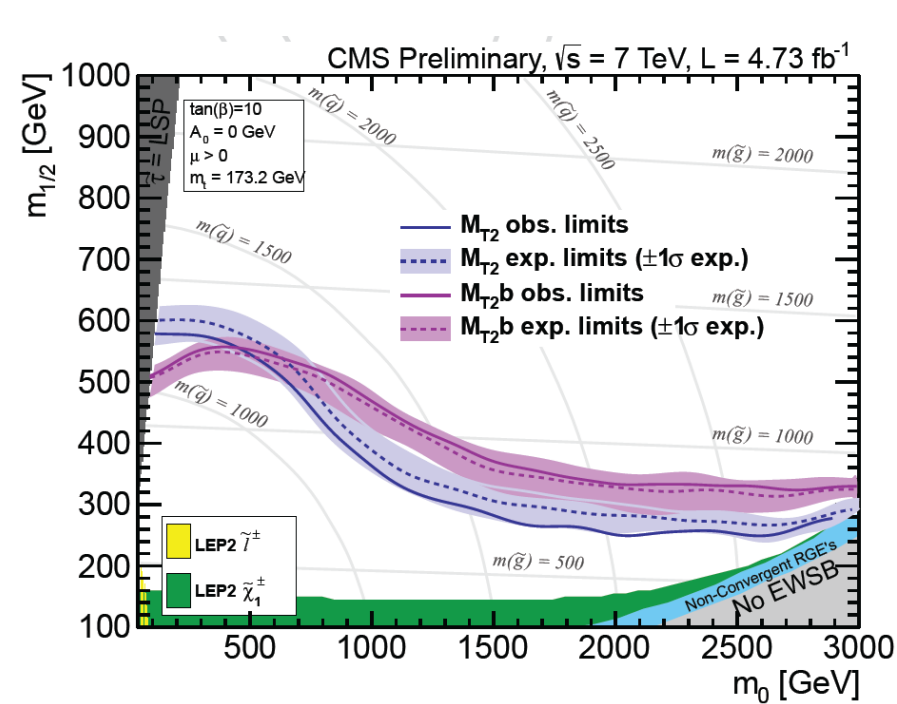
MT2 Search Results



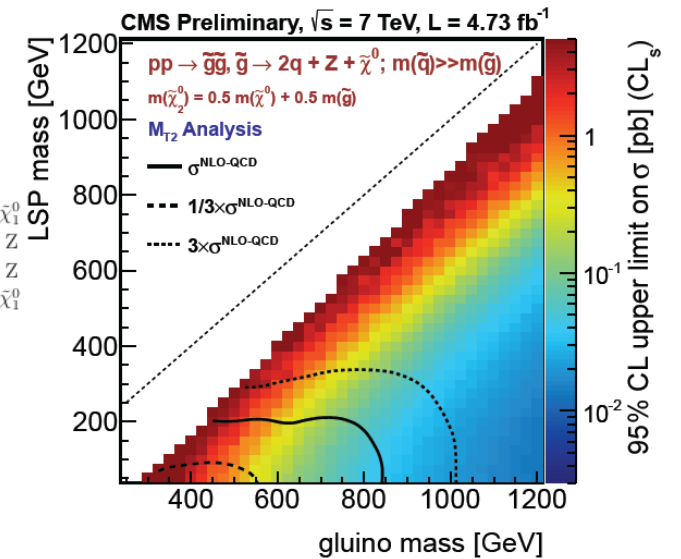
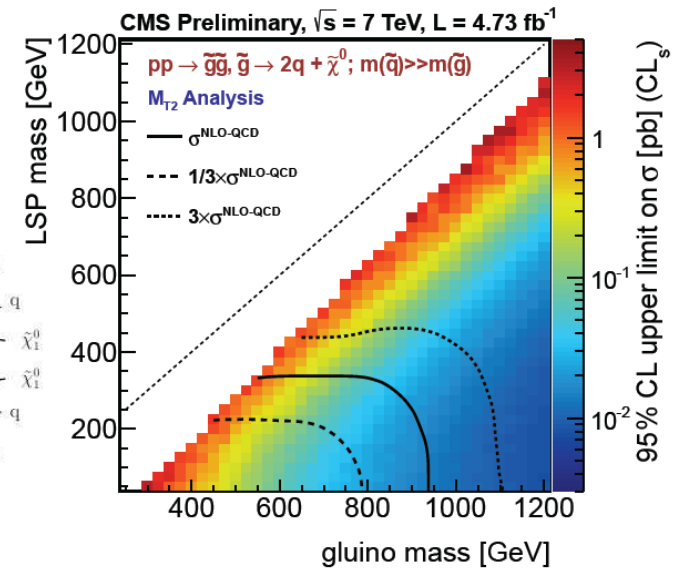
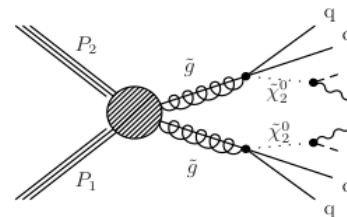
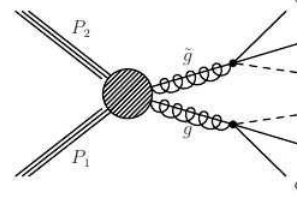
Observations
consistent with
SM expectations

M_{T2} bin	$Z \rightarrow \nu\nu$		Lost lepton		$\tau \rightarrow had$	QCD		Total bkg.		Data
	MC	data pred.	MC	data pred.	Estimate	MC	data pred.	MC	data pred.	
$750 \leq H_T \leq 950$										
[150,200)	27.9	24.2 ± 4.9	36.0	29.6 ± 7.1	22.5 ± 5.4	3.1	7.0 ± 3.5	89.5	83.3 ± 10.7	88
[200,275)	20.3	21.8 ± 4.8	17.2	11.9 ± 3.9	12.7 ± 4.2	0.0	1.0 ± 0.5	50.2	47.4 ± 7.5	69
[275,375)	11.6	13.7 ± 3.8	7.1	4.2 ± 1.9	5.4 ± 2.5	0.0	0.14 ± 0.07	24.1	23.4 ± 4.9	19
[375,500)	6.1	4.1 ± 1.6	2.2	1.1 ± 0.9	2.2 ± 1.8	0.0	0.08 ± 0.05	10.4	7.4 ± 2.6	8
≥ 500	3.5	1.8 ± 0.9	1.1	1.2 ± 1.0	0.6 ± 0.5	0.0	0.00 ± 0.00	5.3	3.6 ± 1.4	6
$H_T \geq 950$										
[150,200)	12.9	16.7 ± 3.6	18.7	16.2 ± 5.3	12.7 ± 4.1	9.8	11.0 ± 5.5	54.2	56.6 ± 9.4	70
[200,275)	10.5	4.5 ± 2.0	11.7	10.2 ± 3.7	7.1 ± 2.6	0.47	1.4 ± 0.7	29.8	23.2 ± 5.0	23
[275,375)	6.4	5.7 ± 2.2	5.0	2.9 ± 1.7	3.3 ± 1.9	0.04	0.13 ± 0.07	14.7	12.1 ± 3.3	9
[375,500)	2.5	3.0 ± 1.4	1.1	0.6 ± 0.6	0.9 ± 0.9	0.0	0.06 ± 0.04	4.6	4.6 ± 1.8	8
≥ 500	2.2	2.5 ± 1.5	0.6	0.6 ± 0.6	0.6 ± 0.6	0.0	0.06 ± 0.04	3.4	3.8 ± 1.7	4

Interpretations



Strigent exclusion at low m_0 & high $m_{1/2}$.





Searches with Razor

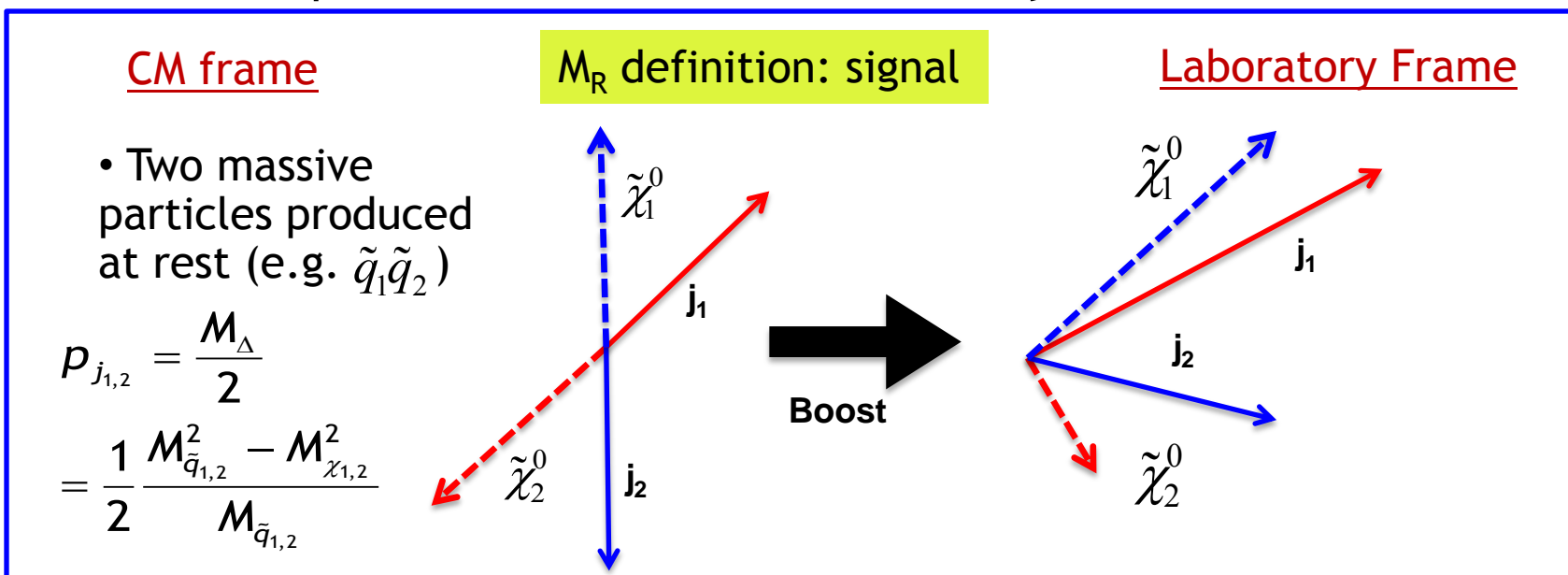


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Razor

Razor search designed to discriminate heavy pair production kinematically from SM backgrounds

- No assumptions on MET or details of decay chain



R frame equalizes 3-momentum of the two jets = *CM frame* if no ISR and sparticles are produced at threshold.

$$M_R = 2p = \sqrt{\hat{s}}$$

M_R peaks for the signal at the mass scale of the heavy particle, M_D

Razor

Razor search designed to discriminate heavy pair production kinematically from SM backgrounds

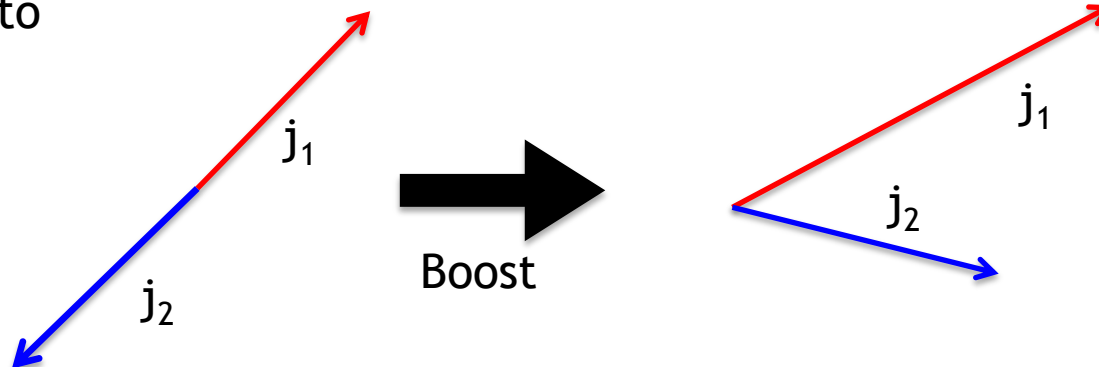
- No assumptions on Met or details of decay chain

CM frame

M_R definition: multijet background

Laboratory Frame

- Two jets back to back



R frame equalizes 3-momentum of the two jets = *CM frame* if no ISR and sparticles are produced at threshold

$$M_R = 2p = \sqrt{\hat{s}} \quad M_R \text{ falls steeply}$$

For the signal, M_R is a measure of the mass of the heavy particle and peaks at the scale of the production

- Maximum of scalar sum of the p_T of the two jets is M_D
- The maximum value of ME_T is also M_D

Real life: multi-jet events → define two hemispheres and combine jets into two mega-jets (force di-jet topology)

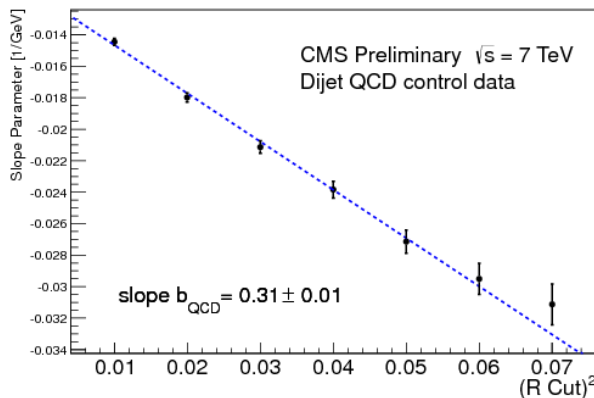
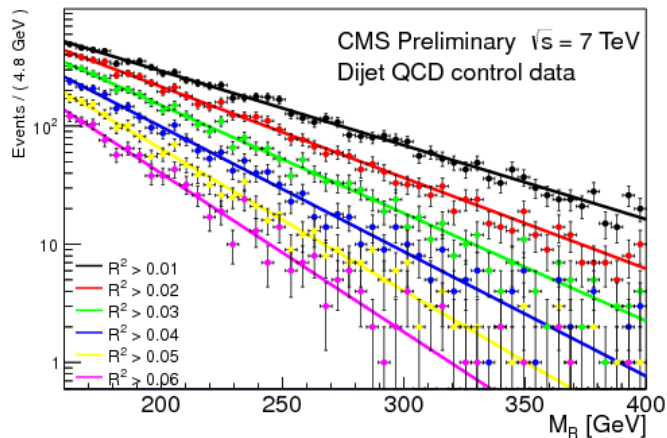
$$M_T^R = \sqrt{\frac{|E_T^{miss}|(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}} \quad \text{Transverse } M_R \text{ has a kinematic edge of } M_D$$

$$M_R = 2 |\vec{p}_{j1}^R| = 2 |\vec{p}_{j2}^R| \sqrt{\frac{(E^{j1} p_z^{j2} - E^{j2} p_z^{j1})^2}{(p_z^{j1} - p_z^{j2})^2 - (E^{j1} - E^{j2})^2}} \quad M_R \text{ peaks at mass scale } M_D$$

$$R \equiv \frac{M_T^R}{M_R} \quad \text{Razor (R) has a kinematic edge of 1, peaks at 0.5}$$

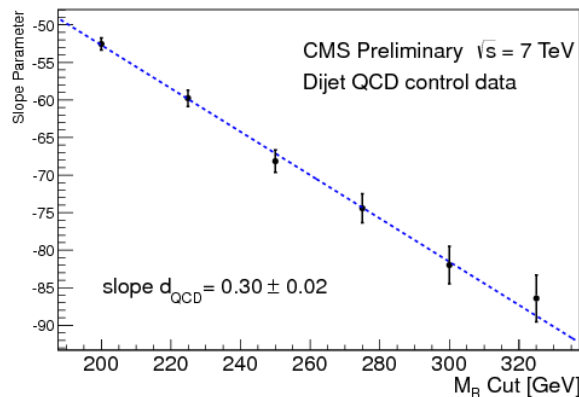
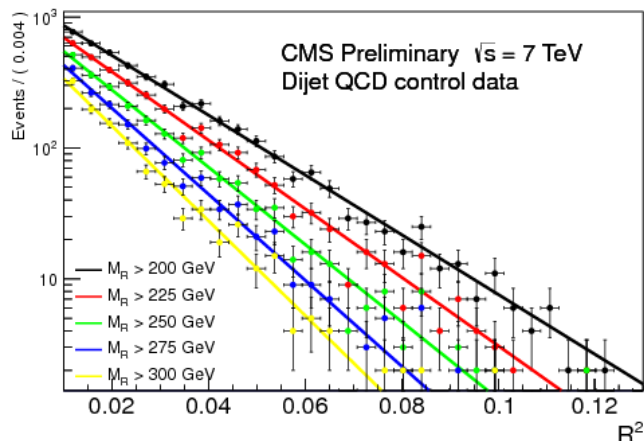
Razor used to separate signal from background

R and M_R Properties



$$f(M_R) \propto e^{-SM_R}$$

$$S = a + b(R \text{ cut})^2$$



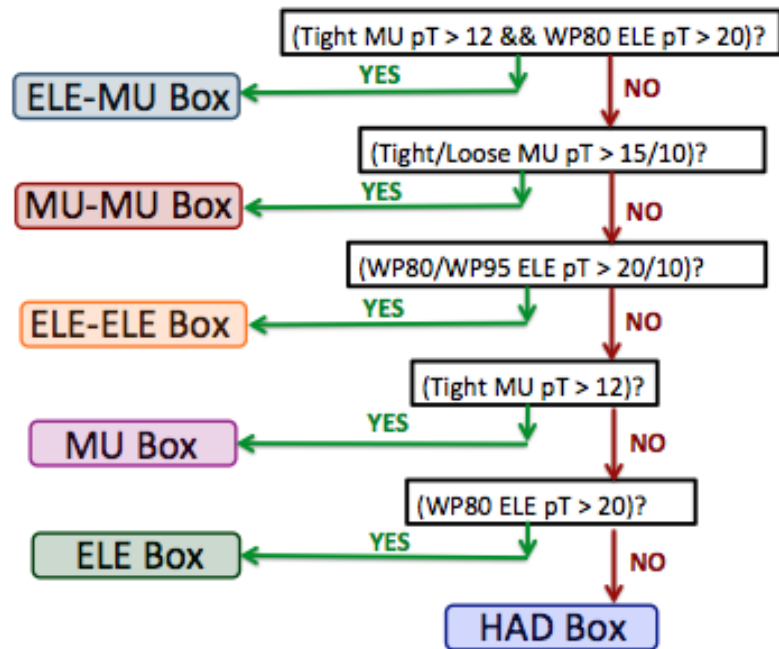
$$f(R^2) \propto e^{-SR^2}$$

$$S = a + b(M_R \text{ cut})$$

$$f(R^2, M_R) \propto [k(M_R - M_R^0)(R^2 - R_0^2)] e^{-k(M_R - M_R^0)(R^2 - R_0^2)}$$

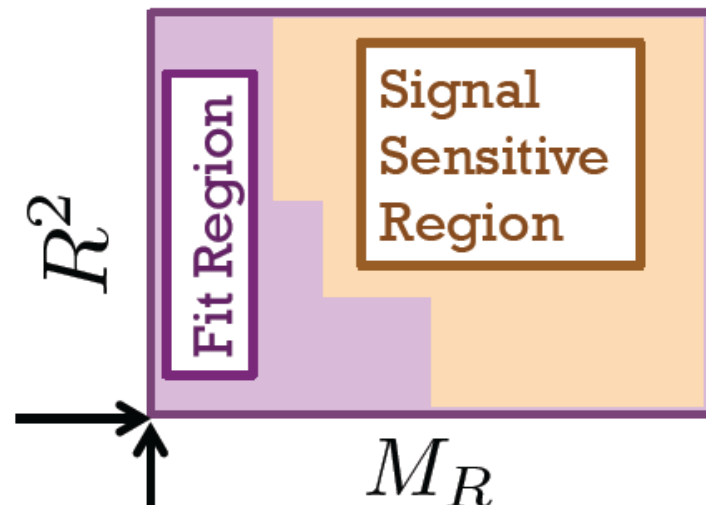
$$b(\text{from } M_R \text{ view}) = d(\text{from } R^2 \text{ view}) = k(\text{from 2D view})$$

“Box” Definitions and Fits



Find state BOX
classification based on lepton ID

Minimum R^2 and
 M_R set by trigger
requirements



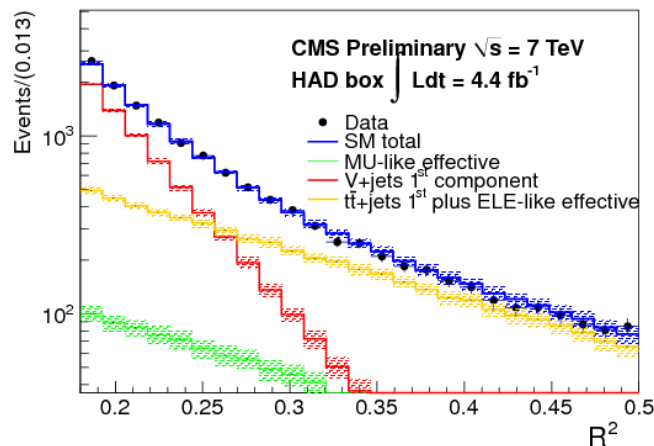
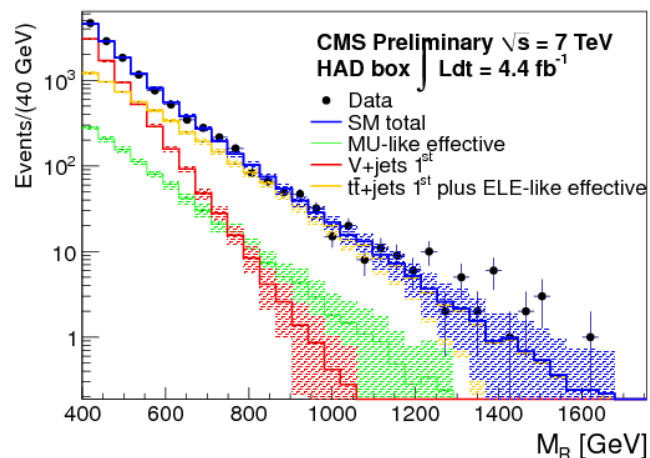
$$\mathcal{L}_b = \frac{e^{-(\sum_{j \in SM} N_j)}}{N!} \prod_{i=1}^N \left(\sum_{j \in SM} N_j P_j(M_{R,i}, R_i^2) \right)$$

Extended and unbinned maximum
likelihood fit performed in 2D R^2 - M_R
plane independently in each BOX

Background functionally extrapolated to signal region

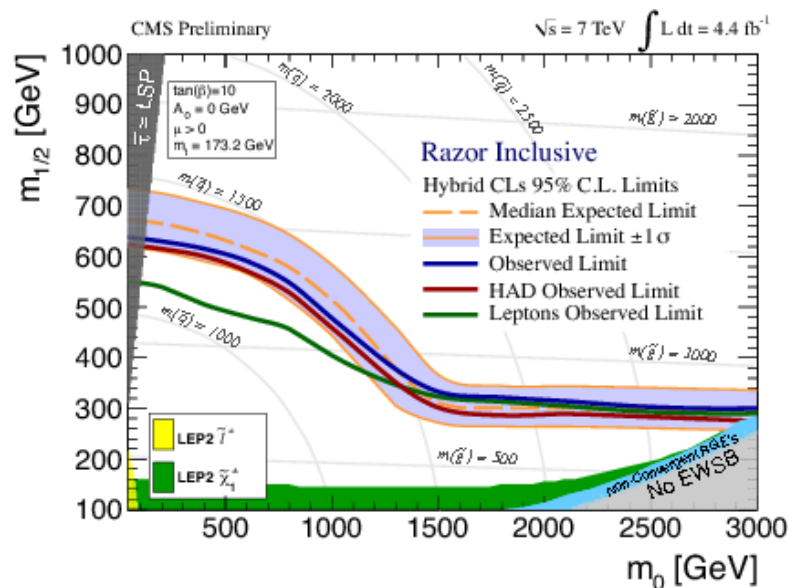
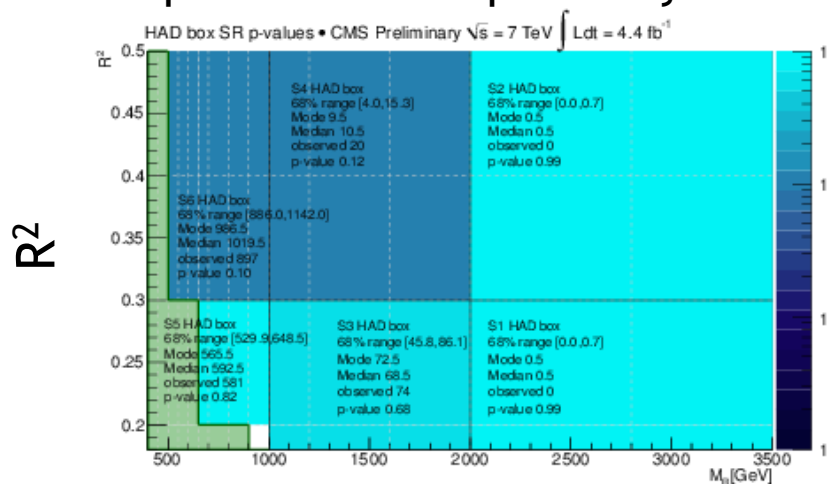
Results

1D projections of 2D ML Fit - HAD Box



Observations
consistent with
SM expectations

Model independent results showing
data/prediction compatibility





Summary

- CMS has performed 3 variants of all hadronic SUSY searches with the full 2011 data
 - Data consistent with the SM backgrounds. Comparable results from different searches.
- Our constraints on the gluinos and 1st generation squarks are getting quite strong:
 - Gluino mass exclusion reaching ~1 TeV depending on the assumptions on other SUSY parameters.
 - The naïve picture with copiously-produced strongly-interacting gluinos and 1st generation quarks is getting disfavored, but we still need to keep looking.
- CMS searches have various ways to improve the search sensitivities for 2012 data analysis:
 - Specifically look at high jet multiplicities - sensitivities to long-cascade models. Reduce systematics for $Z(\rightarrow \nu\nu) + \text{jets}$ BG estimation from $\gamma + \text{jets}$ (close collaboration with theory groups), etc etc.



Backup

